Constellation-X Observations of the Galactic Center

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The Galactic Center is a crucial astrophysical target for several reasons. First, it harbors the nearest low-luminosity active galactic nucleus (AGN), which provides a critical testing site for the physics of accretion at low rates. Second, the region contains 1% of the total stellar mass of the galaxy in a fairly small solid angle (~1.6 square degrees), so that surveys of the region provide a large sample of sources for studying the physics of X-ray production. Third, the continual infall of molecular gas and the subsequent star formation in the region produces unique conditions in the interstellar medium that have surprising manifestations at X-ray wavelengths. Here we provide a sampling of the science topics that *Constellation-X* could address, and discuss how the choice of spatial and time resolution would affect our ability to explore these topics.

A Low-Luminosity Active Galactic Nucleus

The $4 \times 10^6\ M_\odot$ black hole Sgr A* is accreting at a surprisingly low rate. Millimeter polarization measurements place an upper limit on the rotation measure near Sgr A*, which translates to an accretion rate $\dot{M} < 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ (Bower, G.C. et al., 2005, ApJ, 618, L29). The average X-ray luminosity of Sgr A* $L_X = 9 \times 10^{33}$ erg s^{-1} (0.5–10 keV), represents $\approx 10^{-6}$ of the available energy. In fact, with $L_X / L_{Edd} \sim 10^{-11}$, Sgr A* is the most under-luminous black hole yet identified; even quiescent black hole low-mass X-ray binaries produce $L_X \approx 10^{-8}\ L_{Edd}$. This makes it the premier astrophysical target for understanding the physics of accretion at low rates.

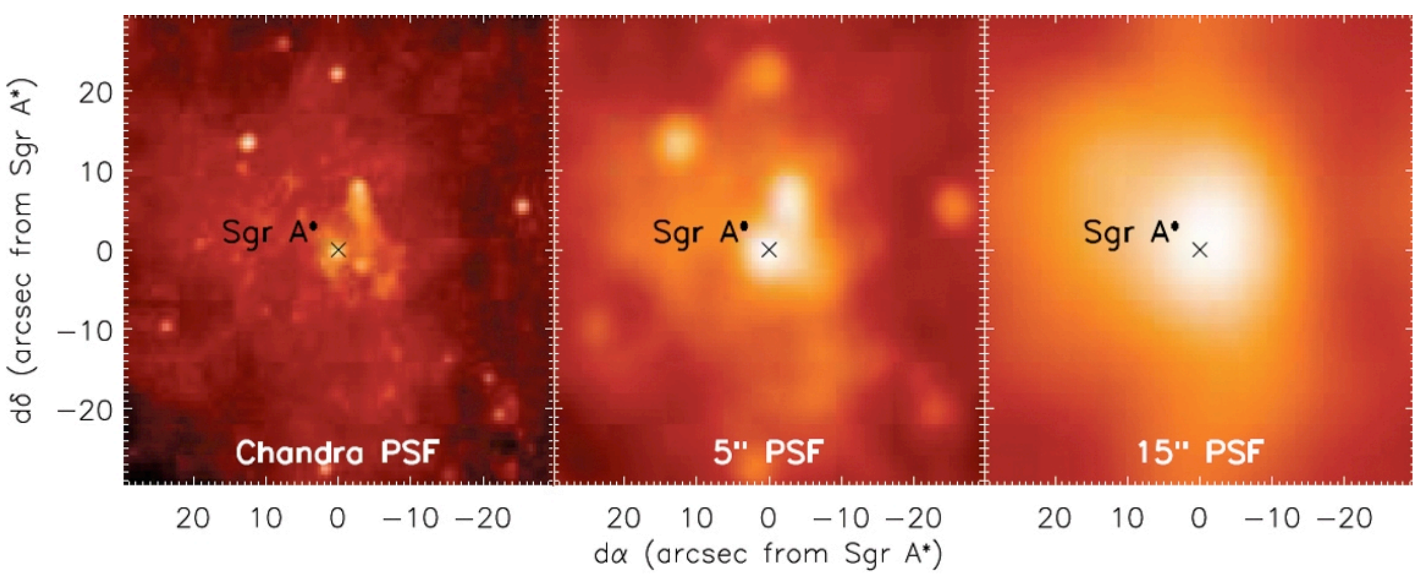

Figure 1: *Chandra* images of the central 2.5 × 2.5 pc around Sgr A*. We display the field at three angular resolutions: 0.5″ to match the *Chandra* PSF, 5″ to match the target resolution of *Constellation-X*, and 15″ to match the minimum required performance of *Constellation-X*. Clearly, an angular resolution of ≈ 5″ is desirable for studying Sgr A*.

Surprisingly, the accretion that does occur is clearly unstable. *Chandra* and XMM observations have revealed that Sgr A* flares by a factor of ten in X-rays for about an hour once a day (Baganoff, F.K et al., 2001 Nature, 413, 45). In one bright are, there even appears to be a quasi-periodic variation in the X-ray ux on time scales of ~20 minutes, which is tantalizingly close to the orbital period of the innermost stable orbit around Sgr A* (Belanger, G. et al., 2005, ApJ, submitted). The nature of these flares is uncertain. They are accompanied by hour-long flares in the infrared (Eckart, A. et al., 2004 A&A, 427, 1), may be related to variability on hour time scales at millimeter wavelengths (Mauerhan, J. C. et al., 2005, ApJ, accepted, astro-ph/0503124) and the optical flares recently discovered from low-luminosity AGN in several distant galaxies (Totani, T. et al., 2005 ApJ, 621, L9). *Constellation-X* observations of Sgr A* will provide the signal required to study the spectra and time variability of these flares in great detail.

In order to achieve its current mass, Sgr A* must have accreted at higher rates in the past. Several features observed at X-ray wavelengths may be evidence of recent active phases from Sgr A*, including an arcminute-scale pair of lobes of X-ray emitting plasma centered on Sgr A* (Baganoff, F. K. et al., 2003, ApJ, 591, 891), a degree-scale radio and X-ray lobe above the Galactic plane that resembles a small version of the bubbles blown in the ISM by starburst activity (Bland-Hawthorn, J. et al., 2003, ApJ, 582, 246), and iron fluorescence nebulae associated with molecular clouds located with 1 of Sgr A* (Murakami, H. et al., 2001, ApJ, 550, 297). *Constellation-X* will have the combination of spectral resolution to determine the emission mechanisms producing these features, and the spatial resolution to separate these features from the other interesting X-ray objects in this crowded region.

A High Density of Rare Objects

The central 300 × 80 pc (2 × 0.8°) contains 1% of the total Galactic stellar mass. Surveys of the region have already identified the largest sample of accreting white dwarfs, neutron stars, and black holes ever obtained (Wang, Q. D. et al., Nature, 415, 148; Pfahl, E. et al., 2002, ApJ, 571, L37; Belczynski, K. et al., 2004, ApJ, 616, 1159; Muno, M. et al., 2004, ApJ, 613, 1179). Many of these accreting compact objects have unique properties, including large-amplitude periodic modulations in their X-ray light curves (Muno, M. et al., 2003c, ApJ, 559, 465), and unusually strong emission from neutral and He-like iron (Muno, M. et al., 2004, ApJ, 613, 1179; Sakano, M. et al., 2005 MNRAS, 3547, 1211). These features provide insight 1 into the physics of X-ray production, how magnetic fields channel accreted material onto compact objects, and radiative transfer in accretion flows. *Constellation-X* will be able to study these features in great detail.

Deep X-ray surveys may also provide the best means of identifying young pulsars near the Galactic center. On order $\sim 10^7 - 10^8$ neutron stars should have formed over the past 10^{10} yr, depending on the initial mass function and the masses of the progenitors to neutron stars. About 20% of these would remain bound to the Galactic center after their supernovae. Pulsars have lifetimes of 10^7 yr so $\approx 10^3$ pulsars are expected to lie within the central 300 pc of the Galaxy. However, no pulsars are currently known in the region, because the high dispersion measure toward the Galactic Center makes their radio pulses difficult to detect (Cordes, J. M. et al., 1997, ApJ, 475, 557). Fortunately, X-ray observations are able to detect young pulsars. Within the first 10^4 yr of a pulsar's life, its rotational energy loss is large enough to power pulsar wind nebulae that can be observed in X-rays (Becker, W. et al., 2002, MPE Report 278, p. 63). Indeed, several compact X-ray sources that resemble pulsar wind nebulae have been identified in the Galactic center with *Chandra* (Park, S. et al., 2005, ApJ submitted). However, in order to confirm that they are pulsars, coherent pulsations must be detected. *Constellation-X* will have the large effective area and millisecond time resolution to make these detections.

Star Formation and the ISM

Within the past 10^7 yr, the Galactic center has been forming stars at a rate of 0.04 $M_\odot$ yr^{-1} (Figer, D. F. et al., 2004, ApJ, 601, 319). The on-going star formation has dramatic manifestations in the *Constellation-X* bandpass.

A hot, 10^8 **K plasma** is observed through emission lines from He- and H-like Fe (Muno, M. P., et al., 2004, ApJ, 613, 326). The high temperature of this plasma is surprising, because it is much hotter than that seen in supernova remnants. Moreover, any Hydrogen with $T \approx 10^8$ K would be too hot to be bound to the Galactic center, so if the plasma is indeed thermal, then it must be composed largely of Helium and heavier ions (Belmont, R. et al., 2005, Nature submitted). *Constellation-X* measurements of the elemental abundances could confirm this hypothesis. Alternatively, the plasma could be produced as a by-product of cosmic-ray acceleration (Dogiel, V. A., et al., 2005, ApJ, 581, 1061). In this case, *Constellation-X* should observe radiative recombination continua from ions in the plasma. Moreover, *Constellation-X* will be able to study the above spectral features on spatial scales of tens of arcseconds, allowing it to determine where the plasma is accelerated.

Young star clusters at the Galactic center have been identified through the X-ray emission from shocks formed both when winds of binary Wolf-Rayet and O (WR/O) stars collide, and when the collective winds encounter the surrounding ISM (Law, C. et al., 2004, ApJ, 611, 858). The Arches cluster is the brightest such object, and exhibits diffuse line emission from neutral iron (Yusef-Zadeh, F. et al., 2002, ApJ, 570, 665). The presence of neutral Fe suggests that the cluster wind is accelerating low-energy cosmic rays, which in turn bombard iron in nearby molecular clouds and it to fluoresce. *Constellation-X* has the right combination of spatial and spectral resolution to study these processes in detail.

The detection of X-ray emission from several synchrotron-emitting radio filaments is one of the most surprising *Chandra* results on the Galactic center – in some cases, it suggests that the filaments are producing TeV electrons (Yusef-Zadeh, F. et al., 2005, astro-ph/0502260). The filaments have been explained as threads of a large-scale magnetic field that are illuminated by interacting with molecular clouds (Morris, M. et al., 1996, ARA&A, 34, 645), magnetic instabilities formed in the wakes of in-falling molecular clouds (Shore, S.N. et al., 1999, ApJ, 521, 587), or shocks in out flows produced by massive stars (Yusef-Zadeh, F. et al., 2004, astro-ph/0403201). The first model assumes that ~1 mG fields are present in the Galactic Center, whereas the latter two assume < 0.1 mG fields. The larger fields also are expected if the gas fed into the Galactic Center carries with it magnetic fields, so distinguishing between these models is crucial for understanding whether fields build-up or are destroyed in the nuclei of Galaxies.

Feasibility

The ability of *Constellation-X* to study the Galactic center will depend largely on the spatial resolution of its optics. We have evaluated the feasibility of studying the above topics based on observations of the Galactic Center with *Chandra*. We scaled the count rates by noting that most photons will be received with $E > 2$ keV (absorption removes lower-energy photons from the Galactic center), and that the effective area of *Constellation-X* between 2–10 keV (6000 cm^{-2}) will be a factor of ≈ 20 larger than that of *Chandra* ACIS (≈ 300 cm^{-2}).

Constellation-X will be able to isolate Sgr A* from the background diffuse emission well enough for us to search for flares. Figure 1 compares the images of the central parsec around Sgr A* that would be obtained with angular resolution of 0.5″(*Chandra*), 5″ (*Constellation-X* target), and 15″ (*Constellation-X* minimum). The background fluxes in regions of various sizes centered on Sgr A* from our *Chandra* images are listed in Table 1. Extracting 90% of the photons from Sgr A* would require a region about four times larger than the half-power diameter (HPD) of the PSF. A flare is detectable at a significance S if the counts it contains (F) exceeds those in the background emission (B) by $F = S/B^{1/2}$. The counts received are related to the photon flux (f) of the source by $F = f\,tA$, where t is the flare duration, and A is the effective area (an identical relation applies to b). Therefore, we can solve for a minimum flux level at which a are is detectable,

$$f = \frac{Sb^{1/2}}{(tA)^{1/2}}$$

We list the flux level at which a flare is detectable in Table 1. *Constellation-X* will be just as sensitive as *Chandra* to detecting flares, and will provide a factor of 20 more photons per flare. However, for a detailed timing and spectral analysis, the background flux must be no larger than that from the flare. Therefore, 5″ resolution is required to provide timing and spectral analysis of 3 the flares, which have $f \approx 4 \times 10^{-4}$ photon cm^{-2} s^{-1}.

Table 1: Detecting Flares from Sgr A*

Mission	$d_{\rm HP}$ (arcsec)	$r_{\rm ext}$ (arcsec)	A cm^2	b ph cm^{-2}	f s^{-1}
Chandra	0.5″	1″	300	3×10^{-5}	2×10^{-5}
Constellation-X	5″	10″	6000	3×10^{-4}	2×10^{-5}
Constellation-X	15″	30″	6000	3×10^{-3}	3×10^{-5}

We list the mission, the half-power diameter, the extraction radius, the effective area, the background diffuse emission, and the photon flux required to detect a 5000 s flare at 5σ. Note that 10^{-5} photon cm^{-2} s$^{-1} \approx 5 \times 10^{-14}$ erg cm^{-2} s^{-1}.

Likewise, *Constellation-X* will provide detailed spectral and timing information on a significant number of sources with uxes larger than the local background. In Figure 2, we display the *Chandra* image of the central 12′ × 12′ of the Galaxy, smoothed to angular resolutions of 5″ (left) and 15″ (right). With 5″ resolution, many of the features in the image, such as point sources, Fe Kα fluorescence nebulae, and the radio- and X-ray-emitting 4′ south of Sgr A*, can be isolated easily from surrounding point sources and diffuse emission. With 15″ resolution, these features are more dif cult to distinguish from their surroundings.

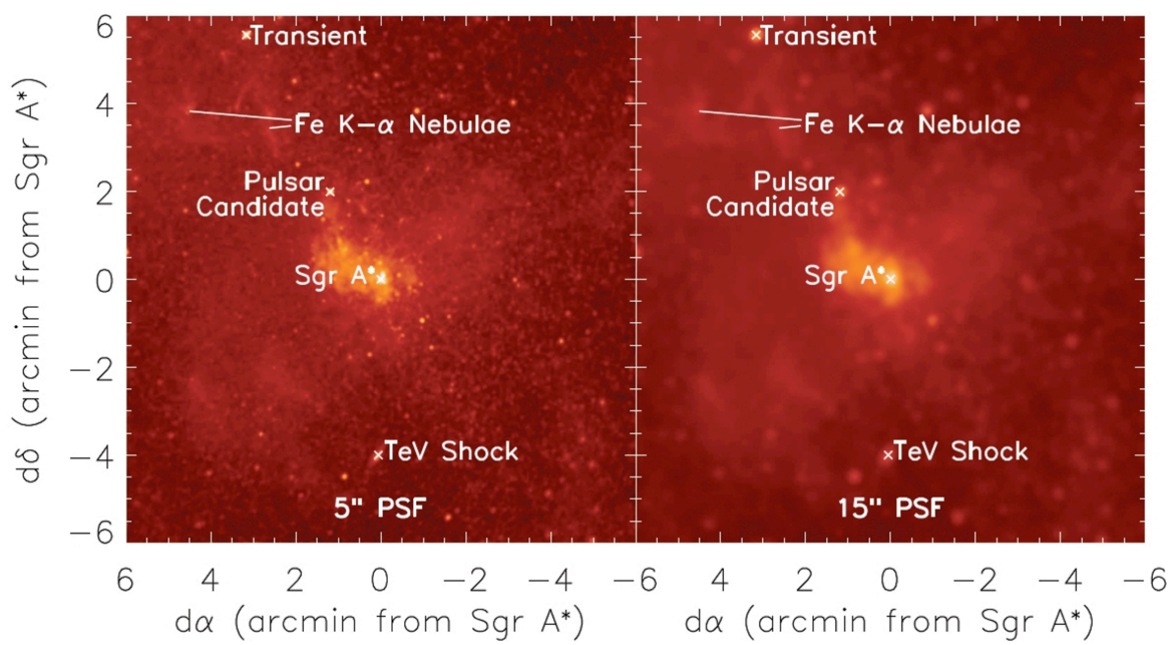

Figure 2: *Chandra* images of the 28 × 28 pc around Sgr A*, smoothed to resolutions of 5″and 15″. An angular resolution of ≈ 5″ reveals many more of the point sources and filamentary features in the field.

We find that the diffuse X-ray background from the Galactic center provides the strictest limit 4 to the fluxes of sources that *Constellation-X* can detect and study.[1] In Table 2, we compare the flux at which observations would be background-limited for different choices of angular resolution. For the background count rates, we assumed $F_X \approx 8 \times 10^{-17}$ erg cm^{-2} s^{-1} arcsec^{-2}, as is appropriate for the central 20 pc of the Galaxy (Muno, M. P. et al., ApJ, 613, 326). Table 2 lists the limit at which sources can be detected.

As mentioned above, for spectral and timing studies, a larger extraction area will be required to enclose most of the source photons, so detailed studies will require sources a factor of several brighter than the limits in Table 2. For a 5″ PSF, spectra will be obtained for sources with $F_X \geq 10^{-14}$ erg cm^{-2} s^{-1}, while for a 15″ PSF sources must have $F_X \geq 10^{-13}$ erg cm^{-2} s^{-1}. For reference, the number of sources in our *Chandra* image scales with flux as $N(>S) \propto S^{-1.3}$ (Muno, M. P. et al., 2003a, ApJ, 589, 225), so *Constellation-X* will be able to study a factor of 20 more sources with a 5″ PSF than with a PSF. 15″

Table 2: Background Limit Near the Galactic Center

Mission	d_{HP} (arcsec)	A cm^{-2}	C_{det} (counts)	b cs^{-1}	t_b	F_b erg cm^{-2} s^{-1}
Chandra	0.5″	300	15	1×10^{-6}	15 Ms	2×10^{-17}
Constellation-X	5″	6000	20	2×10^{-3}	10 ks	2×10^{-15}
Constellation-X	15″	6000	50	2×10^{-2}	2.5 ks	3×10^{-14}

C_{det} is the number of counts required to detect a source, based on synthetic-star simulations using the *Chandra* PSF, b is the background count rate within the HPD of the PSF, t_b is the time at which the number of background counts equals the number of source counts, and F_b is the flux at which an observation would be background-limited. We have assumed a median photon energy of 3 keV, and an energy-independent effective area A. Note that the background limit for spectral extraction is on order 16 times higher, since the 90% encircled energy radius is twice the HPD.

Based on the numbers in Table 2, we can evaluate the angular resolution needed to pursue some tantalizing results produced with *Chandra*. For instance, Park et al. (Park, S. et al., 2005, ApJ submitted) have identified a source that could be the neutron star ejected from the supernova that produced Sgr A* East. The source has $F_X = 2 \times 10^{-13}$ erg cm^{-2} s^{-1}, so a 250 ks *Constellation-X* observation would yield 6×10^4 photons. This would allow one to search for pulsations with 4% rms amplitudes, regardless of angular resolution. This is an order of magnitude smaller than the current upper limits from *Chandra* and XMM.

Using *Chandra*, Muno et al. (Muno, M. P. et al., 2004, ApJ, 613, 1179) also detected iron emission at 6.4 and 6.7 keV from 35% of sources brighter than $\approx 10^{-14}$ erg cm^{-2} s^{-1} (64 of 181 sources). The median flux in the iron line was $I \approx 7 \times 10^{-7}$. Therefore, the spectrum

[1] The diffuse X-ray background should dominate the detector background, and the confusion limit is a factor of several fainter than the background limit.

from a 250 ks *Constellation-X* observation would contain ≈100 photons in the iron complex, which would allow one to derive plasma densities from the He-like triplet and constrain the velocity of the iron-emitting material. However, the diffuse background also produces iron emission with a surface brightness of $\approx 8 \times 10^{-8}$ 10 photon cm^{-2} s^{-1} arcsec^{-2}. For a 5″ HPD PSF with $r_{\rm ext} = 10''$, the background flux should be only $I_{\rm bkg}$ photon cm^{-2} s^{-1}, making a spectral study feasible. However, for a 15″ HPD PSF $r_{\rm ext} = 30''$, $I_{\rm bkg} \approx 2 \times 10^{-6}$ photon cm^{-2} s^{-1}, which is larger than the line flux from the source. Therefore, a 5″ PSF is required to take full advantage of the spectral resolution of *Constellation-X* when studying sources near the Galactic center.

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